

DISCHARGE LAMP TECHNOLOGIES

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INTRODUCTION

This talk is an overview of discharge lamp technology commonly employed in general lighting, with emphasis on issues pertinent to lighting for plant growth. Since the audience is primarily from the plant growth community, and this begins the light source part of the program, we will start with a brief description of the discharge lamps. Challenges of economics and of thermal management make lamp efficiency a prime concern in controlled environment agriculture, so we will emphasize science considerations relating to discharge lamp efficiency. We will then look at the spectra and ratings of some representative lighting products, and conclude with a discussion of technological advance. A general overview of discharge lighting technology can be found in the book of Waymouth (1971). A recent review of low pressure lighting discharge science is found in Dakin (1991). The pioneering paper of Reiling (1964) provides a good introduction to metal halide discharges. Particularly relevant to lighting for plant growth, a recent and thorough treatment of high pressure Na lamps is found in the book by deGroot and vanVliet (1986). Broad practical aspects of lighting application are thoroughly covered in the IES Lighting Handbook edited by Kaufman (1984).

DISCHARGE TYPES

It is helpful to view discharge light sources from the perspective of the ubiquitous incandescent lamp, whose tungsten filament is heated by the passage of electric current, and cooled by radiation. The filament temperature, about 2800 K, is a compromise between the desires to have longer life (cooler filament) and higher efficiency (hotter filament). At the melting temperature of tungsten, 3655 K, its life would be very short indeed.

A discharge light source, shown schematically in Figure 1, changes the game entirely. Electric current heats a gaseous plasma formed between two electrodes and contained within an arc tube. The plasma is incapable of *burning out* in the sense of the incandescent filament, and operates at substantially higher temperatures where it is a more efficient radiator. Life is limited by phenomena at the electrodes and arc tube walls. A typical discharge light source has roughly an order of magnitude advantage in both efficiency and life when compared to its incandescent counterpart.

Important physical characteristics of common lighting discharge types are summarized in Table 1. In each case, the arc tube is characterized by its wall material, internal diameter, gap between electrode tips, and wall temperature. An average power density or loading is simply the total power divided by the volume between the electrode tips. In most cases there are at least two gaseous species present, one of which has the dominant partial pressure, and the other of which is responsible for the radiation. The gas is further characterized by an operating pressure and center temperature. The gas is ionized to create electrons, which gain energy from the electric field, and lose energy to collisions with atoms in the gas. Some of these collisions create excited atoms which in turn radiate releasing photons. It is useful to characterize the electrons by their temperature.

Low Pressure Hg-Ar Discharges

The most familiar form of discharge light source occurs within a fluorescent lamp. The discharge in this lamp is referred to as a low pressure Hg-Ar discharge, which is also found in many neon signs. As indicated in Table 1, the dominant gas is Ar, but the radiation comes from Hg. This radiation is predominantly ultraviolet radiation at 254 nm. The *low pressure* designation signifies that the collision rates are too low for the electrons (11000 K) to reach thermal equilibrium with the gas atoms (300 K). A higher pressure would lead to more collisions and better equilibration. The design of the discharge, however, is chosen to optimize the production of ultraviolet Hg radiation, for which a low pressure is desirable.

TABLE 1 Discharge Lamp Types

Type	Watts Pow (W)	Arctube					Gas		Press. (Atm)	Temperature	
		mat'l	diam (cm)	gap (cm)	loading W/cc	temp (C)	dominant	radiating		gas (K)	elec. (K)
LP Hg-Ar	40	glass	3.6	98.0	0.04	42	Ar	Hg	0.004	300	11000
HP Hg	400	S ₁ O ₂	1.8	8.0	19.65	700	Hg	Hg	2.500	6000	6000
HP MH	400	S ₁ O ₂	2.0	4.3	29.61	800	Hg	Na,Sc	4.000	5000	5000
HP Na	400	Al ₂ O ₃	0.7	8.7	112.92	1150	Hg,Xe	Na	0.900	4000	4000

Visible radiation is produced fluorescence when the ultraviolet radiation strikes a phosphor coating on the inner arctube wall. While the discharge is very efficient at creating ultraviolet radiation, the conversion to visible radiation in the phosphor is inherently inefficient. This is because one ultraviolet photon has sufficient energy to make roughly two visible photons, but due to the quantum nature of the conversion process makes at most one.

High Pressure Discharges

The high pressure discharge lamps in Table 1 are distinguished from the low pressure Hg-Ar discharge by their higher powers, smaller sizes, hotter arctube walls, higher power densities, and higher pressures (The power density or loading, is the power divided by the volume of the cylinder. The cylinder volume defined by the diameter and the arc gap). These high pressure discharges operate very close to thermal equilibrium, with the electron temperature very close to the gas temperature. The centers of these discharges are about 5000 K, close to the temperature of the sun.

In the *high pressure* Hg discharge, Hg is both the dominant gas and the radiating gas. Unlike the low pressure Hg-Ar case, this discharge is designed to optimize the release of visible Hg radiation, predominantly in the 405, 435 and 545 nm lines. Even under optimal conditions, much ultraviolet radiation remains, limiting its visible efficiency.

The high pressure Metal Halide or MH discharge is very closely related to the high pressure Hg. Both involve high pressure Hg in a fused quartz arctube. In the MH case, the arctube also contains small amounts of metal halide salts such as NaI and ScI₃. Under operating conditions, these salts reside as molten condensates on the arctube walls and low concentrations of their vapors are introduced into the gas volume within the tube. Relatively small numbers of Na and Sc atoms in the discharge radiate more readily than do the more numerous Hg atoms. The Na and Sc atoms can do this because their energy levels are lower than

those of the Hg atoms. Furthermore, these Na and Sc energy levels radiate predominantly in the visible rather than the ultraviolet. This gives the MH discharge a higher visible efficiency than the high pressure Hg discharge.

The visible efficiency of the MH discharge can generally be increased either by increasing the power density or by increasing the halide vapor pressure. These approaches go hand in hand with increased arc tube wall temperature. A practical limit is imposed by the fused quartz arc tube material, whose life is severely limited at operating temperatures above 900 C.

The high pressure Na discharge is similar to the MH discharge, involving radiation from Na atoms in the presence of Hg. Here, however, much higher Na vapor pressures are achieved by introducing elemental Na rather than NaI. The polycrystalline Al₂O₃ arc tube material, unlike quartz, is impervious to elemental Na. Furthermore, the Al₂O₃ is able to operate at a much higher (1150 C).

The high pressure Na discharge, like the other two high pressure discharges, has a significant thermal conduction energy loss due to the several thousand degree temperature difference between the core of the discharge and the arc tube walls. This loss could be reduced if the intervening gas had lower thermal conductivity. In fact, Hg vapor is a pretty good insulator, as gases go, owing to its large atomic mass. About the only better choice is Xe. Discharge efficiencies can be increased by using Xe in place of Hg, however this introduces practical problems associated with starting and operating voltage.

LAMP RATINGS AND SPECTRA

Typical Ratings

Ratings of representative commercial lamp types are shown in Table 2. Parameters of most immediate interest for general lighting are the rated life, and the photopic efficacy (plm/W). In both categories, the discharge lamp types all have a considerable edge over the incandescent lamps. The fluorescent and high pressure lamp types have "F" and "HP" designations respectively. More will be said about the "MLX" types later.

TABLE 2 Lamp Ratings

Type	Watts (W)	Life (hours)	Photopic lumens		Plant growth		Scotopic lumens		Vis. eff. Wv/W
			plm	plm/W	RA/plm	RA/W	slm/plm	slm/W	
inc.	100	750	1750	18					
F-CW	40	20000	3150	79	2.08	164	1.50	118	0.22
F-PL	40	20000	800	20	5.86	117	2.87	57	0.14
F-PL/AQ	40	20000	1900	48	3.07	146	1.54	73	0.18
HP Hg	400	24000	21000	53					
HP MH	400	20000	40000	100	2.26	226	1.28	128	0.29
HP Na	400	24000	50000	125	2.13	266	0.63	79	0.31
HP Na	1000	24000	140000	140	2.13	298	0.63	88	0.35
MLX NaNd	400	10000	55000	138	2.25	309	1.78	245	0.42
MLX CsPr	300	10000	33000	110	2.35	259	2.34	257	0.38

Three spectral weighting functions are of interest in evaluating the visible radiation produced by these lamps. These weighting functions are related to the photopic lumen (plm), the scotopic lumen (slm) and the Relative Action for the photosynthetic component of plant growth (RA). The photopic lumen is the most

commonly used lumen and is associated with the color-sensitive cones of the human retina. The scotopic lumen is associated with rods and night vision. The shapes of these weighting functions are shown in Figure 2. All three curves are arbitrarily defined to be 1 at 555 nm, which is the peak of the photopic lumen curve. Light at 555 nm is defined as having an efficacy of 683 plm/W and 683 slm/W.

The RA function in Figure 2 is that reported by McCree (1971) for the average field plant species, and has been normalized here so that $RA = plm = slm$ for 555 nm radiation. Plants show less color discrimination than does the human eye. The RA response is the broadest of the three curves, and is higher in the red where there are more quanta of light per unit of energy. McCree shows, however, that over the 400 to 700 nm range a uniform quantum efficiency does not fit the data much better than does a uniform energy efficiency. The main point to be made with Figure 2 is that lamps developed for general lighting are not necessarily optimal for plant growth.

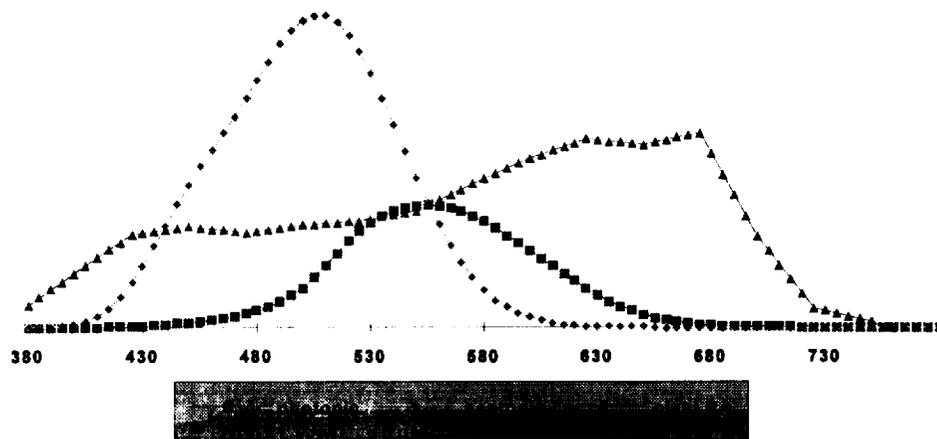


Fig. 2 Spectral weighting functions

Two different measures of power are indicated in Table 2. W represents the total Watts entering the lamp electrically. W_v represents the number of Watts leaving the lamp as visible radiation (380-760 nm). The visible efficiency ratio (W_v/W) shows what fraction of the total power leaves the lamp as visible radiation. The balance leaves primarily as infrared radiation, some emitted by the discharge, but most emitted by various solid components in the lamp assembly. Among the commercial lamp types, the high pressure Na lamps have the best W_v/W ratios.

Spectra

The fluorescent lamp offers enormous opportunity for spectral variation merely through changes in the phosphor. The spectra of three commonly used GE fluorescent lamps are shown in Figures 3-5. Each involves a completely different phosphor system. Figure 3 shows the spectrum of the standard cool white fluorescent lamp. This lamp is commonly found in indoor commercial applications. The spectra shown in Figures 4 and 5 are the result of combining phosphors which have emissions in the far red and blue regions of the spectrum so as to concentrate power near the two peaks in the RA curve shown in Figure 2. These spectra are deficient in green, and make objects appear purple, which is desirable in some circumstances. Table 2 shows that these lamp types have very different RA/W , plm/W and slm/W efficiencies.

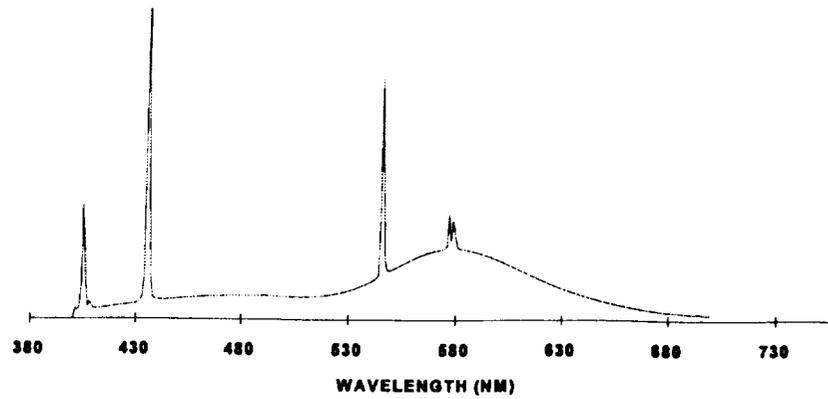


Fig. 3 F-CW Spectrum

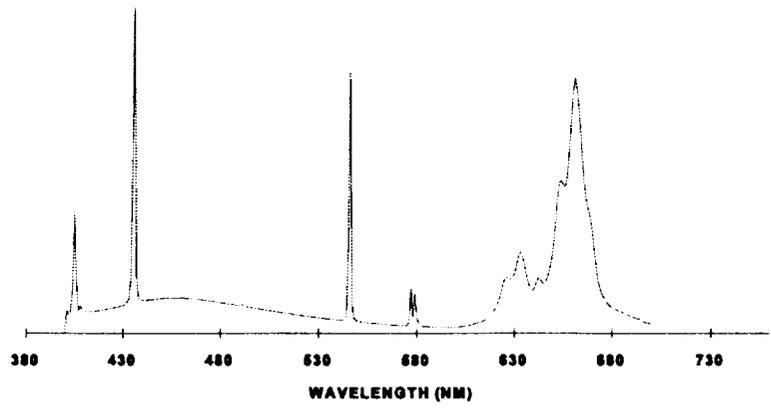


Fig. 4 F-PL Spectrum

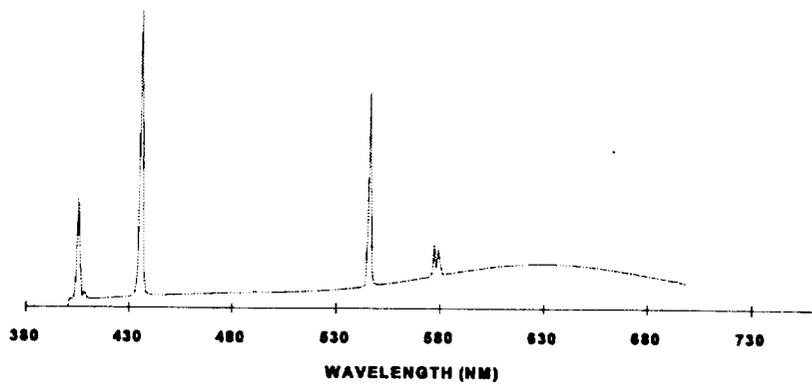


Fig. 5 F-PL/AG Spectrum

The high pressure lamp types are more attractive than fluorescent lamps for many plant growth applications due to their somewhat higher efficiencies, and their ability to provide more light per fixture. The two most important types for plant growth have the spectra shown in Figures 6-7. The high pressure MH spectrum shown in Figure 6 contains prominent Na, Sc and Hg lines which are reasonably well distributed throughout the visible spectrum. MH spectra based on other chemistries are also possible. Many examples are shown in the paper of Reiling (1964). The high pressure Na spectrum shown in Figure 7 contains only Na lines, and is dominated by the self reversed Na resonance line at 589 nm. Table 2 shows the high pressure Na lamp to be more efficient for plant growth, as measured by RA/W, than any of the other conventional lamp types.

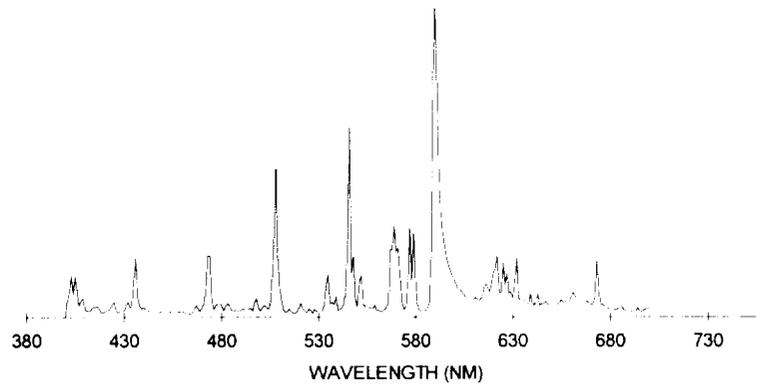


Fig. 6 HP MH Spectrum

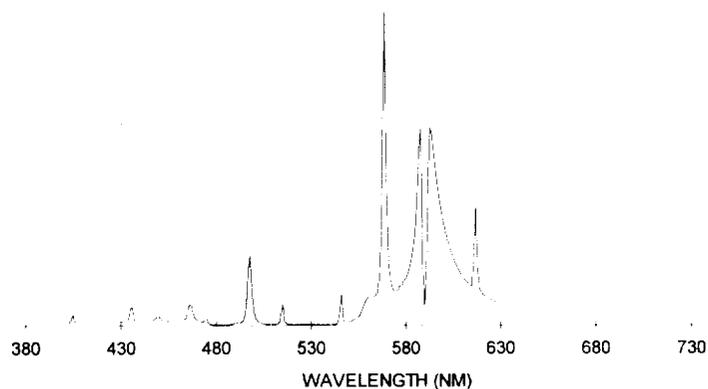


Fig. 7 HP Na Spectrum

Electrodeless High Pressure Lamps

New electrodeless discharge technology being developed at GE, but not now commercially available, offers considerable promise for plant growth. This technology involves a metal halide discharge operating in a fused quartz arc tube without electrodes or Hg. Power is applied by an inductive exciter operating at 13.56 MHz. The lamp configuration is similar to that described by Dakin et al. (1992). Without electrodes, a wider range of halides can be used, and wall blackening associated with tungsten transport is avoided. Two of the many possible halide doses are NaI plus NdI₃ and CsI plus PrI₃. Ratings and spectra achievable with these doses are indicated by the MLX entries in Table 2, and Figures 8 and 9. The CsPr spectrum is populated by myriad Pr atomic lines, with little or no contribution from Cs. The NaNd spectrum has a similar contribution from Nd atomic lines plus the strong Na lines seen earlier in Figure 7. The NaNd system is seen to be more efficient than high pressure Na systems by all measures, and to provide more blue radiation as well.

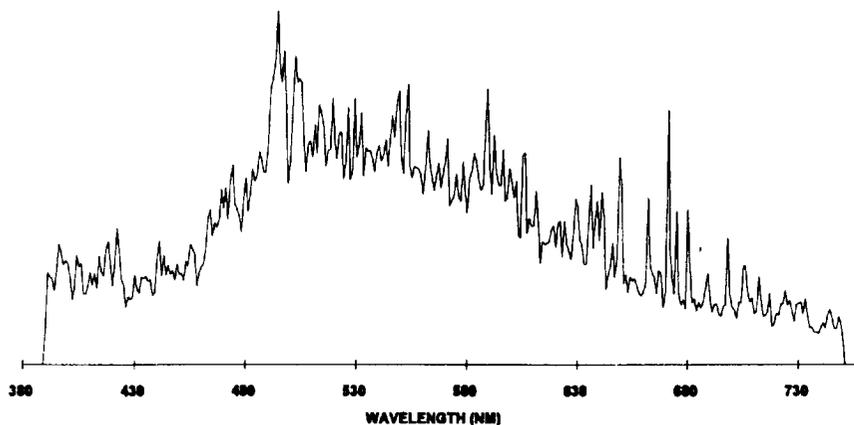


Fig. 8. MLX CsPr Spectrum

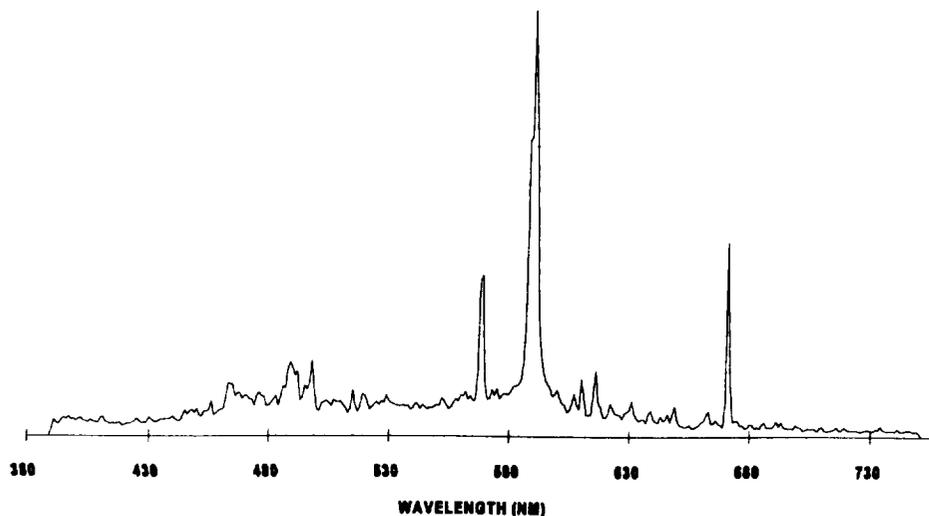


Fig. 9. MLX NaNd Spectrum

ADVANCES

For more than a century, technological advances have enabled the electric lighting industry to steadily introduce better products. That trend continues today. In the incandescent, fluorescent and high pressure categories, new products are available with significant performance advantages over the more familiar types indicated in Table 2. We will quickly review some of the technological advances which are making these new products possible.

Materials

Materials have long had center stage in lighting advances. This is due to fundamental life-performance tradeoffs related to material operating temperatures. A landmark historical advance was the development of translucent polycrystalline Al_2O_3 , which made the high pressure Na lamp possible. A more recent advance is fluorescent lamp phosphors capable of operating at higher temperatures. Another is high temperature dichroic films capable of trapping infrared radiation inside an incandescent lamp while allowing visible radiation to escape.

Ballasting and Electronics

Discharge lamps require ballasts, shown schematically in Figure 1, to limit and control the current which they draw from the electric mains. These ballasts have traditionally been passive electromagnetic devices made of copper and iron, the simplest example being a series inductor. Recent advances in power semiconductors and control circuitry have enabled the development of cost effective electronic ballasts. These typically operate at high frequency, and are smaller, lighter and more efficient than their electromagnetic predecessors. The electronics also enable simple control features such as dimming, and more specialized control features related to idiosyncrasies of the discharge lamps. As shown by Osteen (1979), for instance, the blue emission from the high pressure Na lamp can be enhanced by operating on a pulsing ballast with suitable frequency and duty cycle. Electronic ballasting is quite common in new fluorescent installations, and is beginning to appear for low power high pressure lamp types.

New Lamp Types

A number of new discharge lamp types have appeared in recent years. These have been made possible by new technology, and encouraged by market forces such as energy conservation. The most conspicuous new types are the compact fluorescent lamps with integral ballasts. These are direct replacements for screw-in incandescent lamps, offering the cost and energy savings inherent to fluorescent lighting without the need to install new fixtures. Compact fluorescent lamps with integral ballasts represent a tour de force of new technology, relying on advances in phosphors, electronics, high speed manufacturing, and more. Other new discharge lamp types include a proliferation of low wattage high pressure Na and MH lamps.

More relevant to plant growth are new high pressure Na types with higher efficiency, brought about by increasing the Xe pressure. Other high pressure Na types of possible interest in plant growth operate at higher Na pressure to provide more blue radiation, but at the expense of reduced overall efficiency.

CONCLUSIONS

The lighting industry provides a wide range of commercial discharge lamp types, each offering a unique combination of wattage, efficiency and spectral power distribution. Only a small fraction of the available lamp types have been indicated here. Most of these lamps have been developed for general lighting, where the costs of technological advance are justified by large markets for better products. Many of these same lamps are applicable to plant growth, however, where the spectral requirements are somewhat different than those for human vision. Of particular interest in lighting for plant growth are new fluorescent lamp phosphor systems, ongoing advances in the high pressure Na lamp, and the introduction of new types such as the electrodeless high pressure lamp.

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